[Reprinted from THE SCIENTIFIC MONTHLY, March, 1921]

HISTORY OF BIOLOGY*

By Dr. LORANDE LOSS WOODRUFF
PROFESSOR OF BIOLOGY, YALE UNIVERSITY

SOME practical acquaintance with plants and animals undoubtedly formed the chief content of the mental equipment of prehistoric man, and a considerable knowledge of agriculture and medicine was possessed by the Egyptians and Sumerians nearly 7,000 years ago. So biology has a very ancient pedigree. But biology as the science of life—the study of living phenomena for their own sake in which emphasis is shifted from the practical to the philosophical—really begins with the Greeks, and reaches per saltum a height which was not surpassed, indeed not again attained, for nearly twenty centuries.

Science reaching Greece from the South and East fell upon fertile soil, and in the hands of the Hellenic natural philosophers was organized into coherent systems through the realization that nature works by fixed laws—a conception foreign to the Oriental mind and the cornerstone of all future work because it gave purpose to personal scientific investigation. This attitude of approach is largely responsible for the transformation of the Greek scientific heritage from a collectivistic to an eponymous product.[1] It is not an exaggeration to say that to all intents and purposes the Greeks laid the foundations of the chief subdivision of natural science and, specifically, created biology, though the term biology was first used by Lamarck and Treviranus at the beginning of the nineteenth century.[2]

Aristotle, (384-322 B. C.) the most famous pupil of Plato and dissenter from the Platonic School, represents the highwater mark of the Greek students of nature and is justly called the Father of Natural History. Aristotle's contributions to biology are manifold. He took a broad survey of the existing facts and welded them into a science by relying, to a considerable extent, on the direct study of organisms and by insisting that the only true path of advance lay in accurate observation and description. But mere observation without interpretation is not science. Aristotle's generalizations—his elaboration of broad philosophical conceptions of organisms give to his biological works their perennial significance. Among the facts and supposed facts, and

*Delivered at Yale University, April 29, 1920; the third lecture of a series on the History of Science, given under the auspices of Yale Chapter of the Gamma Alpha Graduate Scientific Fraternity.

[1]E. Clodd: Pioneers of Evolution, 2d ed., 1907, pp. 29-32. C. Singer: Studies in the History and Method of Science, 1917.

[2]Lamarck: Hydrogéologic, 1802. G. R. Treviranus: Biologie, oder Philosophie der lebenden Natur für Naturforscher und Aerzte, 1802-22.

of course there are innumerable crudities if for no other reason than that adequate apparatus and biological technique were of the distant future, there are interspersed questions, answers, theories which show a recognition and remarkable grasp of fundamental biological problems. A study of Aristotle's works shows ancient pedigrees for some of the most "modern" questions of biology, though it is undoubtedly true, as Sachs insists, that one must continually inhibit the tendency to read the present viewpoint into the past, and not assign to earlier writers merits which, if they were alive, they themselves would not claim.

We have not mentioned a single discovery made by Aristotle—and with purpose. Aristotle's position as the founder of biology rests chiefly on his viewpoint and his methods. Plato relied on intuition as the basis of knowledge. Aristotle emphasized observation and induction, insisting that errors arise not from the false testimony of our sense organs but from false interpretations of the data they afford. "We must not accept a general principle from logic only, but must prove its application to each fact; for it is in facts that we must seek general principles, and these must always accord with facts from which induction is the pathway to general laws."[3] But it is not to be imagined that Aristotle always followed his own advice; few great men do—"no pilot can explore unsurveyed channels without a confidence which sometimes leads to disaster." It must be admitted that Aristotle frequently lapsed into unbridled speculation which tended to obscure the methods that time has shown produce the most enduring results, though, as Huxley has well said, "It is a favorite popular delusion that the scientific enquirer is under a sort of moral obligation to abstain from going beyond that generalization of observed facts which is absurdly called 'Baconian' induction. But any one who is practically acquainted with scientific work is aware that those who refuse to go beyond fact, rarely get as far as fact; and any one who has studied the history of science knows that almost every step therein has been made by the 'Anticipation of Nature,' that is, by the invention of hypotheses, which, though verifiable, often had very little foundation to start with; and not infrequently, in spite of a long career of usefulness, turned out to be wholly erroneous in the long run."[4]

7 While Aristotle's biological investigations were devoted chiefly to animals, his pupil and co-worker, Theophrastus (370-286 B. C.), made profound studies on plants, and the list of botanical facts which he observed and in many cases discovered includes nearly all the rudi-

[3]Aristotle: History of Animals, I, 6. H. F. Osborn: From the Greeks to Darwin, 1894, pp. 16-17, 47. T. H. Huxley: On Certain Errors Respecting the Heart Attributed to Aristotle, 1879 (Coll. Sci. Memoirs, IV, pp. 380-392); G. H. Lewes: Aristotle; a Chapter in the History of Science, 1864, pp. 108-13. T. E. Jones: Aristotle's Researches in Natural Science, 1912. W. Whewell: The Philosophy of Discovery, 1860.

[4]T. H. Huxley: The Progress of Science, 1887 (Coll. Essays, vol. 1, p. 62.)

ments of scientific botany. It is a remarkable fact that many details in plant anatomy, which were figured by the pioneers with the microscope, are to be found in the pages of Theophrastus.[5] He not only laid the foundations of botany, but also gave suggestions of much of the superstructure; an achievement which entitles him to rank as "the first of real botanists in point of time."[6]

With the Greeks, then, biology emerged from the shadows of the past and took concrete form—a fact which apparently the discerning mind of Aristotle appreciated since, though frequently referring to the ancients, he writes:

> I found no basis prepared; no models to copy. . . . . Mine is the first step, and therefore a small one, though worked out with much thought and hard labor. It must be looked at as a first step and judged with indulgence.

Before leaving the Greeks we must mention Hippocrates (460-370 B. C.), the Father of Medicine. Writing a generation before Aristotle, at the height of the Age of Pericles, Hippocrates crystallized the knowledge of medicine into a science, dissociated it from philosophy, and gave to physicians "the highest moral inspiration they have." "To him medicine owes the art of clinical inspection and observation, and he is, above all, the exemplar of that flexible, critical, well-poised attitude of mind, ever on the lookout for sources of error, which is the very essence of the scientific spirit. . . . The revival of the Hippocratic methods in the seventeenth century and their triumphant vindication by the concerted scientific movement of the nineteenth, is the whole history of internal medicine."[7]

Medicine, the most important aspect of applied biology, is the foster parent of zoology and botany since a large proportion of biological advances have been the work of physicians. Until relatively recently the schools of medicine afforded the only training, and the practice of medicine the chief livelihood for men interested especially in general biological problems.[8] The history of medicine and of biology, as a so-called pure science, are so inextricably interwoven that the consideration of one involves that of the other. Indeed the physicians form the only bond of continuity in biological history between Greece and Rome. The chief interest of the Romans lay in technology, and therefore it is natural that the practical advantages to be gained would ensure the advance of medicine.[9] As it happens, however, two Greek physicians were destined to have the most influence: Dioscorides, (c. 64 A. D.), an army surgeon under Nero, and Galen (131-201 A. D.), physician to the Emperor Marcus Aurelius and his son, Commodus.

Just as Theophrastus established botany as a pure science, so

[5] E. L. Greene: Landmarks of Botanical History, 1909, pp. 52, 53, 140-142.
[6] A. Haller: Bibliotheca Botanica, I, 31.
[7] F. H. Garrison: History of Medicine, 2d ed., 1917, p. 82.
[8] T. H. Huxley: The Connection of the Biological Sciences with Medicine. Nature, 24, 1881, pp. 342-46; (Also in Coll. Essays).
[9] W. Libby: An Introduction to the History of Science, 1917, Chapter 3.

Dioscorides was the originator of the pharmacopoeia, writing, as he did, not only a work which was the first one on medical botany, but one which, gaining authority with age, was the sole standard "botany" for fifteen centuries. Theophrastus was long overshadowed. Most of the botanical writings up to the seventeenth century were annotations on the text of Dioscorides.[10]

Galen was the most famous physician of the Roman Empire and his voluminous works represent both the depository for the anatomical and physiological knowledge of his predecessors, rectified and worked over into a system, and a vast amount of original investigation. Galen was a practical anatomist who described from dissections and insisted on the importance of vivisection and experiment, and therefore may be considered the first experimental physiologist and the founder of experimental medicine. Galen gave to medicine its standard anatomy and physiology for fifteen centuries.[11]

Any consideration of the biological science of Rome would be incomplete without a reference to the vast compilation of fact and fiction, indiscriminately mingled, made by Pliny the Elder (23-79). It was beside the path of biological advance, but long the recognized "Natural History," passing through some eighty editions after the invention of printing. Its prestige was largely due to the fact that it was written in Latin whereas the great works on biological subjects were in Greek.[12]

For all practical purposes we may consider that biology at the decline of the Roman Empire was represented in the works of Aristotle, Theophrastus, Dioscorides, Galen, and Pliny. Even these exerted little influence during the Middle Ages, being saved from total loss for future generations chiefly by Arabian scientists, and in the monasteries of Italy and Britain. We cannot pause to consider the various causes which resulted in the almost complete break in the continuity of learning in general and science in particular during the dormant period in western Europe.[13] Suffice it to say that contributing factors were wars and rumors of wars, the destruction of the libraries of Alexandria, the antagonism of Christian and pagan ideals, and the establishment by the Church, which held the gates of learning, of the written word in place of observation of nature as it is. "Truth and science came to mean simply that which was written, and inquiry became mere interpretation."

In so far as science was taught at all it was from small compilations of corrupt texts of ancient authors interspersed with anecdotes and fables. Under theological influence there arose the oft-quoted

[10] Greene, op. cit., pp. 151-154.

[11] M. Foster: Lectures on the History of Physiology, 1901. Garrison, op. cit., p. 97-101. M. Verworn: General Physiology, English trans., 1899, pp. 8-11.

[12] F. E. Hulme; Natural History Lore and Legend, 1895, pp. 20-29. Greene, op. cit., pp. 155-159.

[13] A. D. White: History of the Warfare of Science with Theology in Christendom, 1898. Clodd, op. cit., p. 34. Russell, op. cit., pp. 124 et seq,

Physiologus,[14] found in many forms and languages, which is at once a collection of natural history stories, and a treatise on the medicinal use of animals and on symbolism. The centaur and the phoenix take their place with the frog and crow in affording illustration of theological texts and in pointing out more or less evident morals. The line of demarkation between the Physiologus and the Bestiaries into which it gradually evolved is ill defined, while the remnants of the latter are incorporated in the early works of the Renaissance encyclopaedists.[15]

So low had science fallen that, strange to say, the scientific Renaissance may be said to owe its origin to the revival of classical learning and to the translation and study of the writings of Aristotle and others which had been under eclipse for a millennium. These were so superior to the existing science, if it may be dignified by that name, that, in accord with the spirit of the time, Aristotle and Galen became the bible of biology. The first works were merely commentaries on the classical authors, but as time went on more and more new observations were interspersed with the old until elaborate and voluminous treatises describing all known forms of plants and animals were produced. In short, the climax of the scientific Renaissance involved a turning away from the authority of Aristotle and an adoption of the Aristotelian method of observation and induction.

Botany was the first to show visible signs of the awakening, probably because of the dependence of medicine on plant products. "All physicians professed to be botanists and every botanist was thought fit to practice medicine." The Hortus Sanitatis, in a way the botanical counterpart of the Bestiaries, gave place to the Herbals.[16] At the hands of the Herbalists of Germany during the sixteenth century, such as Brunsfels, Tragus, Fuchs, and Valerius Cordus, we can trace the evolution of plant description and classification from mere annotations on Dioscorides to well illustrated manuals of the flora of western Europe.[17]

During the same century zoology made abortive attempts to emerge as a science, but the less immediate utility of the subject combined with the difficulty of collecting material and therefore the necessity of more dependence on traveler's tales, all contributed to retard its advance.

One group of naturalists, the Encyclopaedists, so-called from their endeavor to gather all possible information of living things, attempted the impossible. Gleaning from the ancients and adding such materials as they could collect led to the production of huge books of fact and fancy whose value bore no just proportion to the vast expenditure of labor, even in the case of the best—Gesner's Historia Animalium,

[14] White, op. cit. Also, F. Lauchert: Geschichte des Physiologus, 1889.
[15] Hulme, op. cit., pp. 31, 50.
[16] A. Arber: Herbals; their Origin and Evolution. A Chapter in the History of Botany. 1912.
[17] Greene, op. cit., pp. 164 et seq.

which appeared volume by volume between 1551 and 1587, and comprised some 4,500 folio pages of text and wood cuts.[18]

Although Gesner (1516-1565) was without doubt the most learned naturalist of the period and perhaps the best zoologist that had appeared since Aristotle, the direct path to progress was blazed by men whose plans were less ambitious than those of the Encyclopaedists. Thus, contemporaries of Gesner, men who were befriended by him, such as Rondelet (1507-1566) who gave descriptions of the fishes of the Mediterranean based for the most part on his own observations, and Belon (1517-1564) who illustrated the fishes and birds which he saw in France and the Levant, really instituted the zoological monograph which has proved the productive method of biological study.[19]

Even while the Herbalists, Encyclopaedists and Monographers were at work in natural history, making brave attempts to develop the powers of independent judgment which were oppressed to such an extent during the Middle Ages that the very activity of the senses seemed stunted, the emancipator of biology from the thraldom of the ancients appeared in the Belgian anatomist Vesalius (1514-1564). Disgusted with the anatomy of the time which consisted almost solely in interpreting the works of Galen by reference to crude dissections made by barber's assistants, Vesalius set his hand to the task of placing human anatomy on the firm basis of exact observation, and his great work De Humani Corporis Fabrica makes the year 1543 the dividing line between ancient and modern anatomy.[20] Galen's similar attempt failed because his followers made a bible of his work; but with Vesalius, the time was opportune and, in spite of the opposition of his former teacher Jacobus Sylvius and his pupil Columbus, thenceforth anatomical as well as biological investigation in general broke away from the yoke of authority and men began to trust their own eyes. His successor at Padua, Fallopius, says that Vesalius "so shewed me the true path of inquiry that I was able to walk along it still farther than had been done before."

The work of Vesalius is on anatomy, and physiology is treated somewhat incidentally, though it is evident that he was no better satisfied with Galenic physiology than with Galenic anatomy. The complementary work on the side of function came in 1628 with the publication of Harvey's tract, Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus. No rational conception of the economy of the animal organism was possible under the influence of the Galenic system, and it remained for Harvey (1578-1657) to demonstrate by a series of experiments, logically planned and ingenuously executed,

[18]L. C. Miall: The Early Naturalists, their Lives and Work, 1912, pp. 47-50.
[19]Miall, op. cit. pp. 40-47.
[20]W. Stirling: Some Apostles of Physiology, 1902, pp. 2-5. M. Foster, op. cit., p. 2.

that the blood flows in a circle from heart back to heart again, and thus to supply the background for a proper understanding of the dynamics of the organism as a whole. A new picture of the function of the blood was presented which quickly led to the discovery of the lymphatic system, and gave content to the study of the nutrition of the body.[21]

Harvey's use of distinctively quantitative factors is so important in its establishment of the experimental method in biology that his own statement is of great historical interest:

> I frequently and seriously bethought me, and long revolved in my mind, what might be the quantity of blood which was transmitted, in how short a time its passage might be effected, and the like; and not finding it possible that this could be supplied by the juices of the ingested aliment without the veins on the one hand becoming drained, and the arteries on the other hand getting ruptured through the excessive charge of blood, unless the blood should somehow find its way from the arteries into the veins, and so return to the right side of the heart; I began to think whether there might not be a motion, as it were, in a circle. Now this I afterwards found to be true; and I finally saw that the blood, forced by the action of the left ventricle into the arteries, was distributed to the body at large, and its several parts, in the same manner as it is sent through the lungs, impelled by the right ventricle into the pulmonary artery, and that it then passed through the veins and along the vena cava, and so round to the left ventricle in the manner already indicated. Which motion we may be allowed to call circular.[22]

With the work of Vesalius and Harvey, biologists had again laid hold of the great scientific tools—observation, experiment, induction, which since have not slipped from their grasp.

The Microscopists

Even while the marshalling of accurate descriptions of plants and animals was getting under way, and the study of microscopic anatomy and physiology was making rapid strides forward, an event occurred which was destined to make possible modern biology. This was the adaptation of the principle of the spectacles—the invention, probably by Roger Bacon, of convergent lenses, and therefore of the simple microscope. Then came the compound microscope as a development of the telescope at the hands of Galileo about 1610, and by the end of the century simple and compound microscopes were being made by opticians in the leading centers of Europe.[23]

The earliest clear appreciation of the importance of studying nature with instruments which increase the powers of the senses in general and the vision in particular, is found in a remarkable book, the "Micrographia" of Robert Hooke (1635-1703), published by the Royal Society of London in 1665, which is a demonstration of the advantages to be gained by the use of artificial devices of precision in studying

[21] J. G. Curtis: Harvey's Views on the Use and Circulation of the Blood, 1915. T. H. Huxley: William Harvey, Fortnightly Review, 23, 1878 (Also Coll. Sci. Mem., Vol. 4, p. 319).

[22] Harvey: De Motu Cordis et Sanguinis, English trans. by R. Willis, 1848. (See reprint in "Everyman's Library," pp. 55-56.)

[23] Miall, op. cit., p. 136.

nature. "The next care to be taken, in respect to the senses, is a supplying of their infirmities with instruments, and, as it were, the adding of artificial organs to the natural; this in one of them has been of late years accomplished with prodigious benefit to all sorts of useful knowledge, by the invention of optical glasses. . . . . It seems not improbable, but that by these helps the subtiliety of the composition of bodies, the structure of their parts, the various texture of their matter, the instruments and manner of their inward motions, and all the other possible appearances of things, may come to be more fully discovered. . . . . ."[24]

Although the work is replete with singular anticipations of the discoveries and inventions of other workers in various branches of science, the biologist's interest is chiefly in Hooke's application of his improved compound microscope to the study of plants and animals which paved the way for the more special, profound, and methodical studies of the contemporary students of nature. In the Micrographia are clearly described and figured for the first time the "little boxes or cells"[25] of organic structure, and his use of the word "cell" is responsible for its application to the protoplasmic units of modern biology. It is fair to say that the influence of the Micrographia permeated the sciences in various directions and the illustrations of microscopic objects were copied for nearly two centuries.[26]

The Micrographia was a mere incident in the varied interests of Hooke, while van Leeuwenhoek (1632-1723) spent a long life in studying nearly everything which he could bring within the scope of his simple lenses. Fascinated with the "world of the infinitely little," with a virgin field before him, and no literature on the subject to divert his energies, he was able year after year to send letters to learned academies, chiefly the Royal Society of London, describing what of necessity were discoveries. He saw the Bacteria—he is the first bacteriologist—the Infusoria—he is the first protozoologist—Yeast cells, Rotifers, Hydra; but the list is too long.[27] However, all of Leeuwenhoek's work is by no means dusultory. He displayed much ingenuity in studying the flow of blood through capillaries of the web of the frog's foot and bat's wing, the viviparous reproduction in aphids, the development of fleas, the dessication of rotifers. And all the time he was looking for evidence against the idea of spontaneous generation, being convinced "it is fully proved that no living creature is produced by corruption or putrefaction."[28] But Leeuwenhoek's contribution which attracted the most interest was his description of spermatozoa. Brought to his attention by a young physician,

[24]Micrographia, preface.

[25]Micrographia, observation XVIII, pp. 112-116.

[26]L. L. Woodruff: Hooke's Micrographia, American Naturalist, 53, 1919.

[27]Miall, op. cit., pp. 200-223. B. W. Richardson: Disciples of Aesculapius, 1900.

[28]Select Works of A. van Leeuwenhoek, edited by S. Hoole, 1800-7.

Hamm, Leeuwenhoek transmitted the discovery to the Royal Society. His imagination, however, outstripped his observations and he thought he saw evidence of a homunculus within the spermatozoon. Thus he came to regard the sperm as the true germ which had only to be hatched, as it were, by the female. He was thus the first of the school of 'spermists' which opposed the idea of the 'ovists' that all is performed in the egg.[29]

The patience of Leeuwenhoek would have been strained to the breaking point by the studies on insect anatomy made by Swammerdam (1637-1680) and eventually brought together in his Biblia Naturae. Instigated largely by the desire to refute the current notion, supported by certain statements of the great Harvey, that insects and similar lower animals are merely masses of organic matter which have been moulded, as it were, into a definite form, and are without complicated internal organs, Swammerdam spent his life in studies on their structure and life histories.[30] Revealing as he did, by the most delicate technique in dissection, the finest details observable with his lenses, Swammerdam not only set a standard for minute anatomy which, with that of his contemporary Malpighi, was not surpassed until the work of Lyonet and others nearly a century later, but also dissipated, for all time, the conception of simplicity of structure in the lower animals. Swammerdam thus quite naturally added one more argument to those of Redi and others against spontaneous generation:

> That vulgar opinion, . . which ascribes birth and growth of animals to putrefaction and chance, is diametrically opposite to sound reason. . . . in the smallest animals we constantly everywhere find as much order, contrivance, beauty, wisdom, and omnipotence in the Great Architect, as are shown in the viscera of the largest animals. For to these greater animals all others, however minute, are similar in the great respects of brain, nerves, muscles, heart, stomach, intestines, and parts subservient to generation, and to every other useful purpose; so that one might in a manner affirm, that God has created but one animal, though divided into an infinite number of kinds or species, differing from each other in the figures and inflexions, and extensions of their limbs, as likewise in their dispositions, food and manner of living.[31]

Contemporaries of Hooke, Leeuwenhoek, and Swammerdam were two men who may be considered as the pioneer histologists—Malpighi of Bologna and Grew of London. Grew (1641-1712) devoted all his attention to plant structure, while Malpighi, in addition to botanical studies which paralleled Grew's, made elaborate investigations on animals.

The versatility as well as the genius of Malpighi (1628-1694) is illustrated by his studies on the anatomy of plants, the function of leaves, the development of the plant embryo, the embryology of the chick, the anatomy of the silkworm, the structure of glands.[32] Skilled

[29]Phil. Trans. Royal Soc., 142, 1678.

[30]H. Boerhaave: Life of Swammerdam (Preface to the Biblia Naturae) F. C. Miall, op. cit., pp. 174-199. Also Miall's History of Biology, 1911.

[31]Biblia Naturae, English trans. Edited by John Hill, 1758, part 2, p. 71.

[32]Miall, op. cit., p. 145.

in anatomy but with prime interest in physiology, his lasting contribution lies in his dependence on the microscope for the elucidation of problems where structure and function, so to speak, merge—well illustrated by his ocular demonstration of the capillary circulation in the lungs; at once his first and greatest discovery and the first of prime importance ever made with a microscope—since it completed Harvey's work on the circulation of the blood. Malpighi wrote:

"I see with my own eyes a certain great thing. . . . It is clear to the senses that the blood flowed away along tortuous vessels and was not poured into spaces, but was always contained within tubules, and that its dispersion is due to the multiple winding of the vessels."[33]

The microscopists taken collectively created an epoch in the history of biology, so important is the lens for the advancement of the science.[34] Indeed we find that, broadly speaking, its development along many lines during the eighteenth and particularly the nineteenth century has gone hand in hand with improvements in the compound microscope itself and in microscopical technique. Again, the microscopists in general and Malpighi in particular opened up so many new paths of advance that from this period on it is not possible, even in the most general survey, to discuss the development of biology as a whole. The composite picture must be formed by emphasizing and piecing together various lines of work, such as classification, comparative anatomy, embryology, physiology, heredity, and evolution.

Classification

Classification has as its object that of bringing together things which are alike and separating the unlike. It is "discrimination, description, and illustration—the necessary census task which forms the groundwork on which great theories may be built up"[35]—a problem of no mean proportions when a conservative estimate today shows upward of a million species of animals and plants, leaving out of account the myriads of forms represented only by fossil remains. Naturally the earliest classifications were utilitarian, or more or less physiological: edible and harmful, useful and useless, fish of the sea and beasts of the earth. But as knowledge increased, emphasis was shifted to the anatomical criterion of specific differences and thenceforth classification became at once an important aspect of natural history—a central thread both practical and theoretical. Practical, in that it involved the arranging of living forms so that a working catalog was formed which involved nice anatomical discrimination, and therefore the amassing of a large body of facts concerning animals and plants. Theoretical, because in the process botanists and zoologists were impressed, almost unconsciously at first, with the 'affinity' of various

[33]Foster, op. cit., p. 96.
[34]J. Sachs: History of Botany. English translation, 1890, pp. 220-222.
[35]R. L. Praeger, in Oliver's Makers of British Botany, 1913, p. 220.

types of animals and of plants and so were led to problems of their origin.

From Aristotle who emphasized the grouping of organisms on the basis of structural similarities, we must pass over some seventeen centuries, in which the only work of interest was done by the herbalists and encyclopaedists, to the time of Ray (1628-1705) of Cambridge. As a matter of fact, the Theophrastan classification of plants as Trees, Shrubs and Herbs persisted until the end of the seventeenth century. Previous to Ray the term "species" was used somewhat indefinitely, and his chief contribution was to make the word more concrete by applying it solely to groups of similar individuals, which exhibit constant characters from generation to generation. Covering, as Ray's labors did, the classification of both animals and plants, it is probably not an exaggeration to regard him as the seventeenth century precursor of the great Swedish taxonomist, Linnaeus, for whom he paved the way.[36]

Like many another genius, Linnaeus (1707-1778) was a product of his time and, perhaps, one of the very best examples of the fact that "the most original people are frequently those who are able to borrow the most freely"—to see a great deal in what to others appears commonplace. Linnaeus was first and foremost a botanist. Garnering the best the past had to offer in taxonomy and bringing to bear on it his supreme talent for "classifying, coordinating and subordinating," Linnaeus gave botanical students at once a practical method of classification of flowering plants, based chiefly on the number and arrangement of the stamens. At the same time he insisted on brief descriptions and the scheme of giving each kind of organism a name composed of two words, in which the second word indicates the species and the first, the genus, a group of closely similar species. In short, to name an organism is to classify. Linnaeus' success with botanical taxonomy led him to extend the principles to animals and even to the so-called Mineral Kingdom, the latter showing at a glance his lack of appreciation of any genetic relationship between species.[37]

Indeed the terms genus and species to Linnaeus expressed a transcendental affinity since he believed that species, genera, and even higher groups represented distinct, consecutive thoughts of the Creator. Accordingly, the ultimate goal of taxonomy was to determine the so-called scala naturae. Thus, Linnaeus crystallized two dogmas—constancy and continuity of species—which permeated biology and reached, in slightly different form, their high water mark, indeed a reductio ad absurdum, in Agassiz's Essay on Classification a century later—as fate would have it, just a year before Darwin's Origin of Species.[38]

[36]S. H. Vines: Robert Morrison and John Ray, in Oliver's Makers of British Botany, 1913, p. 9.
[37]J. Sachs, op. cit., p. 108. F. C. Miall: History of Biology, p. 66.
[38]Miall, op. cit., p. 157.

Though today Linnaeus' conception of fixity has been replaced by modifiability of species; the affinity which he recognized and expressed in transcendental terms has given place to similarity based on descent, and his artificial classifications have been superceded by natural classifications, which express, or attempt to express, this genetic connection between species—nevertheless, his greatest works, the Systema Naturae and Species Plantarum created an epoch in biological history, and are by common consent the base line of priority in zoological and botanical nomenclature.[39]

An aftermath of Linnaeus' labors must be mentioned. Naturalists in general and botanists in particular were so captivated with the facility which the Linnean system afforded for cataloging, that collecting and naming became a dominant note for nearly a century. The few who employed microscope and scalpel are outstanding figures on the path to progress.[40]

Comparative Anatomy

The first step toward scientific classification was made, as we have seen, by Aristotle in emphasizing anatomical characters as taxonomic criteria, so that to all intents and purposes classification implies comparison of structural details. Indeed Aristotle recognized the unity of structural plan throughout the chief animal groups, and in reference to man he says "whatever parts a man has before, a quadruped has beneath; those that are behind in man form the quadrupeds back." Not only did he appreciate homology, but also correlation of parts and division of labor in the economy of the animal body.[41] And Theophrastus approached plant morphology in the same philosophical spirit—witness his recognition of the flower as a metamorphosed leafy branch.[42] But it probably would be reading too much into the past to assign the origin of comparative anatomy of animals in the modern sense of the term to Greek, Roman, or early Renaissance science, since description rather than comparison was the key-note. The same may be said of the anatomical work of Vesalius, Harvey, and Malpighi though the latter compared the microscopic structure of various organs, and in his Anatomy of Plants, which shares with Grew's Anatomy the honor of founding vegetable histology, emphasizes the importance of the comparative method. Owing to the less marked structural differentiation of plants in comparison with animals, plant anatomy does not lend itself as readily to descriptive analysis so that an epoch in the study of comparative anatomy is less defined in botany

[39]Systema Naturae, 1735, 10 ed., 1758. Species Plantarum, 1753.

[40]F. W. Oliver: Makers of British Botany, 1913, p. 193. For the point of view of the early part of the nineteenth century, cf. W. Swainson: On the Study of Natural History, 1834.

[41]E. S. Russell: Form and Function; A Contribution to the History of Animal Morphology, 1917, Chapter 1.

[42]Greene, op. cit.

than in the sister science. Therefore both reason and expediency warrant confining our attention to the comparative anatomy of animals.

Probably the first consistent attempt to make a comparative study of the form and arrangements of the parts of animals is represented in a volume published in 1645 by Severinus (1580-1656) of Naples in which he concluded that many vertebrates are constructed on the same plan as man, though Belon, nearly a century earlier, figured and compared the skeletons of bird and man side by side "in the same posture, and as nearly as possible bone for bone."[43] Tyson (1650-1708) of Cambridge at the end of the seventeenth century definitely instituted the monographic treatment of comparative morphological problems in his study of the anatomy of man and monkeys.[44]

Comparative anatomy, however, as a really important aspect of biological work, in fact, as a science in itself, was the result of the life work of Cuvier (1769-1832) of Paris during the first quarter of the last century. It is true that his immediate predecessors, such as John Hunter (1728-1793), the founder of the Hunterian Collection, the nucleus of the anatomical Museum of the Royal College of Surgeons in London, Camper (1722-1789) of Groningen, and Vicq d'Azyr (1748-1794) of Paris, added synthesis to analysis and reached a broader view-point in anatomical study, but Cuvier's claim to fame rests on the remarkable breadth of his investigations—his grasp of the comparative anatomy of the whole series of animal forms.[45] And not content merely with the living, he made himself the first real master of the anatomy of fossil vertebrates and as such is the founder of paleontology.[46]

Cuvier's position in the history of anatomy is largely due to his emphasizing, as Aristotle had done before him, the functional unity of organisms—that the interdependence of organs results from the interdependence of function and that structure and function are two aspects of the living machine which go hand in hand. Cuvier's famous principle of correlation—"Give me a tooth," said he, "and I will construct the whole animal"—is really an outcome of this viewpoint. Every change of function involves a change in structure and therefore, given extensive knowledge of function and of the interdependence of function and structure, it is possible to infer from the form of one organ that of most of the other organs of an animal. "In a word, the form of the tooth implies the form of the condyle; that of the shoulder blade that of the claws, just as the equation of a curve implies all its properties."

[43] F. C. Miall: History of Biology, pp. 18-19.
[44] Cf. Garrison, op. cit., p. 240.
[45] Cf. Russell, op. cit., Chapter 3.
[46] T. H. Huxley: The Rise and Progress of Paleontology, Nature, 24, pp. 452-55, 1881. (Also Coll. Sci. Mem. Vol. 4). O. C. Marsh: History and Methods of Paleontological Discovery, Presidential address, Amer. Assn. Adv. Sci., 1879.

Although Cuvier undoubtedly allowed himself to exaggerate his guiding principle until it exceeded the bounds of facts, he was above all in his science and philosophy a hard-headed conservative and autocrat. He opposed with equal vigor the influence of the Naturphilosophie of Schelling and his school with its transcendental anatomy, Platonic archetypes and the like, as well as the evolutionary speculations of Lamarck and his school. From the vantage points of today we know that in one case he was right and in the other wrong—though in so far as the facts then extended, his opposition was justified in both cases.

Cuvier's immediate successors in France were Milne-Edwards and Lacaze-Duthiers; in Germany, Meckel, Rathke, Müller, and Gegenbaur; in England, Owen and Huxley, and in America, Agassiz, Cope, and Marsh Among these, Owen (1804-1892) perhaps demands special mention. At once a peculiar combination of Cuvierian obstinacy in regard to facts and of transcendental imagination, Owen spent a long life dissecting with untiring patience and skill a remarkable series of animal types, as well as in reconstructing extinct forms from fossil remains. Aside from the facts accumulated, probably his greatest contribution was making concrete the distinction between homologous and analogous structures, which has been of the first importance in working out the pedigrees of plants as well as animals—though Owen himself took an enigmatical position in regard to organic evolution.[47]

Physiology

Anatomy emphasizes the static and physiology the kinetic aspect of the organism, though, as we have seen, structure without function is a lifeless subject and function without structure is an impossibility, since, in Huxley's happy phraseology, physiology is the mechanical, and he would now add, chemical engineering of the living organism.

Animal and plant physiology was discussed by Aristotle, but as might be expected since physiology is more dependent than anatomy upon progress in other branches of science, with less happy results. Similarly, Galen was hampered in his attempt to make physiology a distinct department of learning based on a thorough study of anatomy, and the corner stone of medicine. Like Aristotle he attempted to develop a picture of the modus operandi of the organism, and with such success that fate foisted it upon uncritical generations through fifteen centuries. The worst of it was not that it was nearly all wrong, but that to question Galen's physiology or anatomy was little less than sacrilege until the labors of Vesalius and Harvey brought a realization that Galen had not quite finished the work.[48]

[47]Life of Richard Owen, by his grandson, 1894, vol. 2, pp. 89-96. Also, Essay on Owen's Position in Anatomical Science by T. H. Huxley, in above work.

[48]Foster, op. cit., p. 12.

Neither Vesalius nor Harvey made an attempt to explain the workings of the body by appeal to so-called physical and chemical laws; and for good reason. Chemistry had not yet thrown off the shackles of alchemy and taken its legitimate place among the elect sciences, while during Harvey's lifetime, under the influence of Galileo, the new physics arose. But by the end of the seventeenth century both physics and chemistry, aided by the philosophical systems of Bacon and Descartes, had forced their way into physiology and split it into two schools: the iatro-mechanical founded by Borelli (1608-1679), who by incisive physical methods attacked a long series of problems, frequently with brilliant results; and the iatro-chemical school, which developed from the influence of Franciscus Sylvius (1614-1672) as a teacher rather than as an investigator.[49]

This awakening brought a host of workers into the field and the harvest of the century was garnered and enriched by Haller (1708-1777), the "abyss of learning" of the time, in a comprehensive treatise which at once indicated the erudition and critical judgment of its author and established physiology as a distinct and important branch of biological science, rather than a mere adjunct of medicine.[50] Great as was this contribution of Haller in crystallizing physiology and setting the dividing line between the old and the modern, unfortunately the weight of the author's authority was ranged in favor of two theories which were, in crude form, attracting the attention of biologists—the idea of special vital force and the preformation theory of development.

Perhaps the most significant lines of advance in Haller's century were in setting the physiology of nutrition and respiration—both of which waited upon the work of the chemists—well upon their way toward modern form. Réaumur (1683-1757) of Paris, and Spallanzani (1729-1799) of Pavia may be singled out for their exact studies of gastric digestion which, against the background of the pioneer work during the previous century by van Helmont (1477-1644), Sylvius (1614-1672), Stensen (1638-1686), de Graaf (1641-1673), Peyer 1653-1712), and Brunner (1653-1727), established solution of the food as the main factor in digestion, though it was not clear how these changes differed from ordinary chemical ones. So physiologists of a vitalistic turn of mind cloaked their ignorance under the term "animalization," and left for eighteenth century investigators the establishment of the fact that food in passing along the digestive tract runs the gamut of a series of complex chemical substances, or enzymes, each of which has its part to play in putting the various constituents of the food into such a form that they can pass to the various cells of the body.[51]

[49]Foster, op. cit., Chapters 3 and 6.

[50]A. Haller: Elementa Physiologiae Corporis Humani, 1757.

[51]W. B. Johnson: History of the Progress and Present State of Animal Chemistry, 1803.

On the side of respiration a somewhat closer approach was made toward a true understanding of the process, but there was a better foundation on which to build. The Galenic notion that respiration is a process of refrigeration—a getting rid of the innate heat of the heart and of fuliginous vapors—had been superceded, through the efforts of Harveyan experimentalists—the chemist Boyle (1627-1691), the versatile genius Hooke, the physician Lower (1631-1690), and the lawyer-chemist Mayow (1643-1679). The climax only awaited the overthrow of the Stahlian phlogiston theory, which presented an inverted picture of combustion, and the actual discovery of oxygen. This came in the work of Black, Priestley (1733-1804), Lavoisier (1743-1794), and Girtauner (1760-1800) which made it clear that the chemical changes taking place in respiration involve essentially a process of combustion, and it chiefly remained for later work to show that this takes place in the tissues rather than in the lungs.[52]

Enough perhaps has been said to indicate the trend of physiology away from the maze of Galenic spirits in which science lost itself, toward the modern atmosphere of science with its *working hypothesis*, that life phenomena are an expression of a complex interaction of physico-chemical laws which do not differ fundamentally from the so-called laws operating in the inorganic world, and that the economy of the organism is in accord with the law of the conservation of energy —probably the most far reaching generalization of science during the past century. Although it is difficult to discriminate, certainly the names of Liebig, Wöhler (1800-1882), the brothers Weber, Ludwig (1816-1895), Helmholtz (1821-1894), Müller (1801-1858) and du Bois-Reymond (1818-1896) in Germany; Dumas (1800-1884), Magendie (1783-1855) and Bernard (1813-1877) in France; Donders (1818-1889) in Holland; and Hall (1790-1857) in England were, individually and collectively, chiefly responsible for the reformation of physiology.[53]

Most of the firm foundation on which physiology of animals rests today has been built up by work on vertebrates, though since the middle of the nineteenth century, when the versatile Müller showed the value of studying the physiology of higher and lower animals alike, the science of comparative physiology may be said to have been established.[54] Perhaps it is not an exaggeration to say that the tendency to focus evidence, in so far as possible, from all forms of life on general problems of function represents the present trend of physiological enquiry.

[52] J. Loeb: Dynamics of Living Matter, p. 7. O. Hertwig: The Growth of Biology in the Nineteenth Century, Smithsonian Report, 1900, pp. 461-78.

[53] M. Verworn: General Physiology, English trans., 1899, pp. 16-20. Stirling, op. cit., p. 106.

[54] P. B. Hadley: Johannes Müller, Popular Science Monthly, 1908.

The less obvious structural and functional differentiation of plants retarded progress in plant physiology as it did in plant anatomy. Probably of most historical, and certainly of most general interest is the development of our knowledge of the nutrition of green plants.

Aristotle's notion that the food of plants is prepared for them in the ground was still prevalent at the end of the sixteenth century when Cesalpino, the most philosophic botanist of his day, thought that food enters and passes through vessels and fibers of plants much as oil in a lamp wick, and Jung conceded that plants are not mere passive absorbers of ready-made food, but possess the power of selection from the soil the ingredients needed. Van Helmont (1577-1644), on the border line between alchemist and chemist, who precociously brought to bear the chemical point of view on animal physiology, made the first experiment in plant nutrition on record. He planted a small tree in a large vessel and weighed it. Then after five years, during which time it had only been supplied with water, he found that it had increased some thirty fold in weight and "not suspecting that the plant drew a great part of its materials from the air was forced to exaggerate the virtues of rain-water."[55] Malpighi, however, from his studies on plant histology, gave the first hint of the fact of supreme importance that the crude sap, which enters by the roots, is carried to the leaves where, by the action of sunlight, evaporation, and some sort of a fermentation it is "digested" and then distributed as food to the plant as a whole. But, it is Hales (1677-1761) to whom the botanist looks as the Harvey of plant physiology, for in his Vegetable Statics, published in 1727, he laid the foundations of the physiology of plants by making "plants speak for themselves through his incisive experiments." For the first time it became clear that green plants derive an important element of their food from the atmosphere, and also that the leaves play an active rôle in the movements of fluids up the stem and in eliminating superfluous water through evaporation.[56]

Still the picture was incomplete, and so it remained until the biologist had recourse to further data from the chemist. In 1779 Priestley, the discoverer of oxygen, showed that this gas under certain conditions is liberated by plants. This fact was seized upon by Ingen-Housz (1730-1799) who demonstrated that carbon dioxide from the air is broken down in the leaf during exposure to sunlight, the plant retaining the carbon and returning oxygen—the process of carbon-getting being quite distinct from that of respiration in which carbon dioxide is eliminated. It remained then for de Saussure to show, by quantitative studies of the plant's income, that, in addition to the fixation of carbon, the elements of water are also employed while from the soil various salts including the element nitrogen are obtained. But

[55]Thomson, The Science of Life, p. 70.
[56]F. Darwin: Stephen Hales, in Makers of British Botany, 1913, p. 65.

it was nearly the middle of the last century before the influence of Liebig (1803-1873) and the incisive experiments of Boussingault established the fundamental part played by the chlorophyll of the green leaf in making certain chemical elements available to animals. The realization of the cosmical function of green plants—the link they supply in the circulation of the elements in nature—is a landmark in biological progress, and we may leave the subject here since, except for details in regard to some of the more evident chemical products of photosynthesis and the influence of external factors, the matter still stands essentially where it was in de Saussure's day.[57]

Histology

Studies on the physiology of plants and animals naturally involved the progressive analysis of the physical basis of the phenomena under consideration, but the Aristotelian classification of the materials of the body into unorganized substance, homogenous parts or tissues, and heterogenous parts or organs practically represents the level of analysis until the beginning of the last century. It is true, as we have mentioned, that Hooke in 1665 discovered that cork tissue under the microscope seemed to be composed of little boxes or "cells," and somewhat similar though more extensive observations were made by the contemporary students of the microscope. But another century had nearly elapsed before these microscopic elements were looked at from the point of view of their relation to the development of organisms. Wolff (1733-1794) in 1759 attempted to show the falsity of the prevailing idea that all organisms are preformed in the germ and that the adult state is attained merely by an unfolding and enlarging, by a critical study of the development of animals and plants.[58] And he not only proved his point but also showed that both plants and animals in early developmental stages show a similar fundamental structure, "since every organ is composed at first of a little mass of clear, viscous, nutritive fluid, which possesses no organization, but is at most composed of globules. In this semi-fluid mass cavities are now developed; these, if they remain round or polygonal, become the subsequent cells; if they elongate, the vessels; and the process is identically the same, whether it is examined in the vegetating point of a plant, or in the young budding organs of an animal." But Wolff's refutation of preformation, chiefly through the opposition of Haller, proved abortive, and his observations on cells were so far ahead of the times that they had but slight influence on biological advance. It was not until the revival of interest in plant anatomy early in the last century that the cell became a particular object of study—and still it

[57] H. A. Spoehr: The Development of Conceptions of Photosynthesis since Ingen-Housz, Scientific Monthly, 9, 1919, p. 32.

[58] C. F. Wolf: Theoria Generationis, 1759. W. M. Wheeler: Wolff and the Theoria Generationis, Woods Hole Biol. Lectures, 1898, pp. 265-284.

was the cell wall rather than the contents on which attention was fixed. Then the English botanist Brown discovered the cell nucleus in 1831,[59] quickly followed by the classic investigations of the botanist Schleiden (1804-1881) and the zoologist Schwann (1810-1882), published in 1838 and 1839,[60] which taken together clearly showed that all organisms are composed of units or cells which are at once structural entities and centers of physiological activities. Each cell carries on a double life; one a quite independent and self-contained life; the other a dependent life in so far as the cell has become an integral part of the organism. The life of the organism is the life of the individual cells which compose it. And further, not only are all organisms congeries of cells, but the egg is a cell and the development of animals and plants consists in the multiplication of this initial cell into the multitude of different kinds which constitute the adult: "The elementary parts of all tissues are formed of cells in an analogous, though very diversified manner, so it may be asserted that there is one universal principle of development for the elementary parts of organisms, however different, and that this principle is the formation of cells."[61]

Unquestionably the launching of the cell theory represents one of the greatest generalizations in biology, and only needed for its consummation the full realization that the viscid, jelly-like material, which zoologists interpreted as the true living matter of animals, and the quite similar material, which botanists considered the true living part of plants, are practically identical. This conception was grasped in the early sixties by Schultze (1825-1874) in the formulation of the protoplasm theory, and thenceforth not only morphological elements —cells—but also the material of which they are composed—protoplasm —was recognized as fundamentally the same in all living beings. Indeed, the realization of a common physical basis of life in both plants and animals—a common denominator to which all vital phenomena are reducible—gave content to the term biology and created the science of life in its modern form.[62]

Embryology

The enunciation of the cell theory came, as we have seen, from combined studies on the adult structure and on the development of plants and animals from the germ or egg, and accordingly implies that the science of embryology has a history of its own. As a matter of fact, Aristotle discussed the wonder of the beating heart in the hen's egg after three days' incubation, but there the subject practically rested

59 J. B. Farmer: Robert Brown, in Makers of British Botany, 1913, p. 119.
60 M. J. Schleiden: Ueber Phytogenesis, 1838. T. Schwann: Mikroscopische Untersuchungen ueber die Uebereinstimmung inder Structur und dem Wachstum der Thiere und Pflanzen. English translations by H. Smith, 1847.
61 Schwann, op. cit., English trans. p. 165.
62 E. B. Wilson: The Cell in Development and Inheritance, 2d ed., 1900. Verworn, op. cit.

until Fabricius (1537-1619), early in the seventeenth century, published a treatise which illustrated the obvious sequences of events within the hen's egg to the time of hatching.[63] This beginning was built upon by a pupil of Fabricius, the celebrated Harvey, who added many details of interest and insisted, as Aristotle had before him, that the embryo arises as a gradual differentiation of unformed material of the egg.[64]

However, little progress in embryology was possible without the microscope which was first applied to the problem by the versatile Malpighi, in two treatises sent to the Royal Society in 1672.[65] One has but to study his splendid series of illustrations to realize how animal development was placed upon a plane so advanced that for over a century it was unappreciated. One conclusion of Malpighi, however, was seized upon by contemporary biologists. Apparently, unbeknown to him, some of the eggs which he studied were slightly incubated so that he thought traces of the future organism are preformed in the egg. This error, coupled, for example, with Swammerdam's observation of the fact that parts of the adult insect are delineated in the larva ready to pupate, crystallized the preformation theory which denied all true development or epigenesis, as advocated by Aristotle and Harvey, and held that the future adult characters pre-exist in miniature in the egg. Even the acute observations of Wolff in his embryological classic, to which we have referred, failed of fruition since it negated the preformation idea which, in the years that had elapsed since Malpighi, had become the dominant question in embryology. Indeed the theory was carried to a reductio ad absurdum by Haller, Bonnet (1720-1793) and others who accepted the logical conclusion that:

> Each seed includes a plant: that plant, again,
> Has other seeds, which other plants contain:
> Those other plants have all their seeds; and those,
> More plants, again, successively inclose.
> * * * * * * * * *
> So Adam's loins contain'd his large posterity,
> All people that have been, and all that e'er shall be.
>
> Amazing thought! what mortal can conceive
> Such wond'rous smallness! Yet we must believe
> What reason tells: for reason's piercing eye
> Discerns those truths our senses can't descry.

So Baker expressed it in one of the few departures from prose permitted in the Philosophical Transactions of the Royal Society.[66]

The truth of the matter is that the time was not ripe for theories of development. The preformationists were wrong but so were Aristotle, Harvey, and Wolff who went to the other extreme and denied all egg

[63]Locy, op. cit., p. 43. Russell, op. cit., p. 113.
[64]W. Harvey: Exercitationes de Generatione Animalium, 1651.
[65]Locy, op. cit., p. 202.
[66]H. Baker: The Microscope Made Easy, 2d ed., 1743, p. 252.

organization and therefore tried to get something out of nothing. It remained for the present generation of embryologists to work out many of the details of the origin of the germ cells and their organization, and to reach a level of analysis deep enough to suggest how "the whole future organism is potentially and materially implicit in the fertilized egg cell," and thus that "the preformationist doctrine had a well concealed kernel of truth within its thick husk of error."[67]

The real step to progress, Baker's implicit confidence in "reason" to the contrary, came in the accurate and comprehensive studies of von Baer (1792-1876) published in the thirties of the last century.[68] Taking his material from all the chief groups of higher animals von Baer founded comparative embryology. Among his achievements may be mentioned the clear discrimination of the chief developmental stages, as cleavage of the egg, germ layer formation, tissue and organ differentiation; the importance of the facts of development for classification, and the discovery of the egg of mammals. His observations on the origin and development of the germ layers, which afforded the key to many general problems of morphogenesis, and his emphasis on the resemblance between certain embryonic stages of higher animals and the adult stages of lower forms, were exaggerated and crystallized by his successors, under the influence of the evolution theory, as the germ layer theory and the recapitulation theory, or von Baer's law. Both were of the greatest importance in stimulating research for half a century—and if the present generation has not inherited its forebears' implicit faith in the theories, it at least has profited immensely by the facts they accumulated.[69]

From every point of view von Baer created an epoch in embryology synchronous with the formulation of the cell theory by Schleiden and Schwann, and it thenceforth became the problem of the embryologist to interpret development in terms of the cell. Time will not permit us to follow the establishment of the fact that the egg and the sperm are really single nucleated cells; that fertilization consists in the fusion of egg and sperm and the orderly arrangement of their chief nuclear contents, or chromosomes; that the new generation is the fertilized egg since every cell of its body as well as every chromosome in every cell is a lineal descendant by division from the egg, and so from the germ cells which united at fertilization to form it. Such, however, are the chief results of cytological study since von Baer; but embryologists have not been content to employ merely the descriptive method, and the

[67]Thomson, op. cit. C. O. Whitman: Woods Hole Biological Lectures, 1894, pp. 205-272. E. B. Wilson: The Problem of Development, Science, 21, 1905, pp. 281-294.

[68]K. E. von Baer: Ueber Entwickelungsgeschichte der Thiere. Beobachtung und Reflexion, 1828-37. Cf. Huxley: Philosophical Zoology Selected from the Works of K. E. von Baer, in Scientific Memoirs, February and May, 1853.

[69]Locy, op. cit., pp. 214-222.

dominant note of the most modern research under the influence of Roux is physiological—the experimental study of the significance of fertilization, the dynamics of cell division, the basis of differentiation, the effect of environmental stimuli, and so on.[70]

Genetics

It is but natural that the study of inheritance could be little more than a groping in the dark until embryology, under the influence of the cell theory, afforded a body of facts which clearly indicated that the fertilized egg is typically the sole bridge of continuity between successive generations. Indeed the present science of genetics has a history confined solely to post-Darwinian times and mostly to this century.

Although clearly suggested by a number of workers, the conception of the continuity of the germ cells—or germ plasm—was first forced upon the attention of biologists and given greater precision by Weismann (1834-1914) in a series of essays culminating in 1892 in his volume entitled The Germ Plasm. He identified the chromatin material which constitutes the chromosomes of the cell nucleus as the specific bearer of hereditary characters, and emphasized a sharp distinction between the cellular derivatives of the fertilized egg—on the one hand, the somatic cells which by division and differentiations build up the body of a higher plant or animal; and on the other, the germ cells which are destined to play but little part in the life of the individual which bears them, but instead are to be liberated and give rise to the next generation. The importance of this distinction can hardly be over emphasized for at once it makes clear that, for all practical purposes, the bodily characteristics of an individual are negligible from the stand point of heredity, since the offspring are descendants not from the body cells, but from the germ cells which it carries—and these in turn from the germ cells of the preceding generation. As Weismann insisted, this view makes it difficult to conceive how modifications of the soma can so specifically affect the germ cells which it bears that the latter can reproduce the modifications—in other words that so-called "acquired characters" can not be inherited. And there is no satisfactory evidence that such characters are inherited. The practical bearings of this conclusion are obviously of the highest importance, lying as they do at the very root of many questions in regard to the factors of evolution, not to mention such practical ones as education and eugenics.

While this viewpoint has been gradually gaining content and precision, the science of heredity has been advancing not only by exact studies of the structure and physiology of the germ cells, but also by statistical investigations of the results of heredity—the various characters of animals and plants in parent and offspring.

[70]Wilson, op. cit.

The first studies of this type which attracted the attention of biologists were made by Galton (1822-1911), who in the eighties and nineties of the last century amassed a large amount of data in regard, for example, to the stature of children with reference to that of their parents, and formulated his well known "laws" of inheritance.[71] But the epoching making work which eventually created the science of genetics was that of an Austrian monk, Gregor Mendel (1822-1884), who combined in a masterly manner the experimental breeding of pedigreed strains of plants and the statistical treatment of the data thus secured in regard to the inheritance of sharply contrasting characters, such as the flower color in sweet peas. Mendel's work was published in 1865 in an obscure natural history periodical[72] and he himself abandoned his teaching and research to become the Abbot of his monastery. Thus terminated prematurely the productive work of one of the epoch makers of biology, and the now famous "Mendelian laws" of inheritance were unknown to science until 1900 when other biologists, coming to similar results, unearthed his forty-year-old paper. We can pause only to say that the fundamental principle of the segregation of the genes of the alternative characters within the germ cells, which Mendel's work indicated, has been extended to other plants and to animals, and from being, as at first thought, a principle of rather limited application, now seems to be the key to all inheritance. And the present results are extremely convincing because cytological studies on the architecture of the chromosome-complex of the germ cells keep pace and afford a picture of the physical basis—of the mechanism by which the segregation and distribution of characters by the Mendelian formula takes place.[73] Such is the deeply hidden germ of truth in the old preformation theories!

Origin of Life

With our present conception of the complexities of organisms it is difficult to realize that up to the seventeenth century naturalist and layman saw nothing more incongruous in the spontaneous origin of nearly all kinds of plants and animals than does the boy of today who believes that horse hairs soaked in water are transformed into worms. Even Aristotle thought that certain of the vertebrates, such as eels, arose spontaneously, and Harvey accepted the same view of the origin of many forms of life. It remained for Redi (1626-1698) to lay aside discussion for experiment. By protecting decaying meat from contamination by flies he demonstrated that these insects are not developed from the flesh and that the apparent transformation of meat into maggots

[71] F. Galton: Natural Inheritance, 1889.

[72] G. J. Mendel: Versuche über Pflanzen-Hybriden, Verhandlungen des naturforschenden Vereines in Brünn, Bd. 4, 1865.

[73] T. H. Morgan: The Physical Basis of Heredity, 1919.

is due solely to the eggs of flies being deposited thereon.[74] But the time-honored doctrine was not overthrown by this experiment or the long series which Redi made, for the presence of parasites within certain recondite parts of higher animals baffled Redi himself, while improvements in the microscope soon revealed a microcosm whose origin seemed plausibly explained as spontaneous. Biogenesis, or all life from preexisting life, was placed on a secure foundation only within the past sixty years by the working out of the remarkably complex life histories of internal parasites and by the classical demonstrations of Pasteur and others that micro-organism are not the result but the cause of decay; a fact which is at the basis of and is attested by the methods now universally in use in food preservation and aseptic surgery—to mention but two instances.[75] The vicissitudes of the doctrine of biogenesis—" la génération spontanée est une chimère," wrote Pasteur—is an eloquent illustration of the aphorism of the old London microscopist that "the likeliest method of discovering truth is by the observations and experiments of many upon the same subject."[76]

Organic Evolution

Since we have every reason to believe that all life now arises from preexisting life and has done so since matter first assumed the living state, it apparently follows that the stream of life is continuous from the remote geological past to the present and that all organisms of today have an ancient pedigree. This leads us to a question which has interested and perplexed thinking men of all times, how things came to be as they are today? It was the Greek natural philosophers who projected the idea of history into science and attempted to substitute a naturalistic explanation of the Earth and its inhabitants for the established theogenies, and thus started the uniformitarian trend of thought which culminated in the establishment of organic evolution during the past century.

Again it is Aristotle who is singled out among the Greeks for his combination of sound philosophy and induction which reaches no higher expression than in his statements regarding the relationships of organisms. He says, in substance: Although the line of demarcation is broadly defined, yet nature passes by ascending steps from one to the other. The first step is that of plants; which, compared with animals, seem inanimate. The second step nature takes is from plants to plant-animals, the zoophytes. The third step is the development of animals, which arise from an increased activity of the vital principle,

[74]F. Redi: Esperienze Intorno alla Generazione Degl'Insetti, 1668. English trans. 1909.

[75]T. H. Huxley: Biogenesis and Abiogenesis. Presidential Address, British Assn. Adv. Sci., 1870. Collected Essays, Vol. 8, L. L. Woodruff: The Origin of Life, in the Evolution of the Earth and Its Inhabitants, R. S. Lull, editor, 1918.

[76]Baker, op. cit., p. V.

resulting in sensibility; and with sensibility, desire; and with desire, locomotion. Man is the head of animal creation. To him belongs the God-like nature. He is preeminent by thought and volition. But although all are dwarf-like and incomplete in comparison with man, he is only the highest point of one continuous ascent.[77]

Broadly speaking, Aristotle apparently held substantially the modern idea of the evolution of life from a primordial mass of living matter to the highest forms, and believed that evolution is still going on—the highest has not yet been attained. In looking for the effective cause of evolution Aristotle rejected Empedocles' hypothesis of the chance play of forces, which embodied in crude form the idea of the survival of the fittest, and substituted secondary natural laws to account for the fact that "Nature produces those things which, being continually moved by a certain principle contained in themselves, arrive at a certain end." As Osborn points out, Aristotle's rejection of the hypothesis of the survival of the fittest to account for adaptations of organisms was a sound induction from his necessarily limited knowledge of nature—but had he accepted it he would have been "the literal prophet of Darwinism."[78]

Although the thread of continuity of evolutionary thought is not broken from Aristotle to the present, no historical interest will be served in following the poetical expression by Lucretius, the discussion at once broad and narrow of the most liberal medieval Churchmen, the "Arab philosophy—a system of Greek thought expressed in a Semitic tongue and modified by Oriental influences," or the vagaries of the Renaissance naturalists and speculative evolutionists, who, with a minimum of fact and a plethora of imagination were the worst enemies of the evolution idea. In truth, the great natural philosophers from Bacon and Leibnitz to Kant and Hegel laid the broad foundation for our modern attack on evolution, but from the strictly biological viewpoint, two Frenchmen, Buffon and Lamarck, and two Englishmen, Erasmus Darwin and his grandson, Charles Darwin, stand preeminent, and the greatest is Charles Darwin.

Buffon (1707-1778) was a peculiarly happy combination of parlor entertainer and scientist—entertaining by each new volume of his great Natural History the social set of Paris, and instructing them at the same time. And it was largely between the lines of his Natural History that Buffon's evolutionary ideas found expression; but expressed they are, though sometimes difficult to decipher—beyond the ken, Buffon hoped, of the censor and dilettant, for apparently he was not of martyr stuff.[79] It is not strange, therefore, that there are some differences of opinion amongst biologists today as to just how much

[77]Lewes, op. cit., pp. 189-96. Osborn, op. cit., p. 48.

[78]Osborn, op. cit., pp. 55-57.

[79]S. Butler: Evolution Old and New. 3d Edition, 1911, p. 78. A. O. Lovejoy: Buffon and the Problem of Species, Pop. Sci. Monthly, 1911.

weight is to be placed on some of Buffon's statements, but certainly it is not exaggerating to ascribe to him not only the recognition of the factors of geographical isolation, struggle for existence, artificial and natural selection in the origin of species, but also, which is equally important, the propounding of a theory of the origin of variations. He thought that the direct action of the environment brings about modifications of the structure of animals and plants and these are transmitted to the offspring.[80]

When Buffon's influence was at its zenith, Erasmus Darwin (1731-1802), a successful medical practitioner, expressed consistent views on the evolution of organisms in several volumes of prose and poetry.[81] Although a contemporary critic in the Edinburgh Review remarked that Darwin's "reveries in science have probably no other chance of being saved from oblivion, but by having been married to immortal verse," today biologists recognize him as the anticipator of Lamarck's doctrine that variations spring from within the organism through its reaction to environmental conditions. "All animals undergo perpetual transformations which are in part produced by their own exertions, in consequence of their desires and aversions, of their pleasures and their pains, or of irritations, or of associations; and many of these acquired forms or propensities are transmitted to their posterity."[82]

While Cuvier was extending and synthesizing the knowledge of anatomy of living and extinct forms and founding the so-called school of facts, his fellow-countryman Lamarck (1744-1829), on the basis of work first on plants and then on animals, carried on in fearless manner the evolutionary inspiration of Buffon and Erasmus Darwin (though the latter's works may not have been known to him), and established the coterie of evolutionists in Paris each of whose essays Cuvier hailed as a "new folly." Lamarck developed with great care the first complete and logical theory of organic evolution, and is the one outstanding figure in biological uniformitarian thought between Aristotle and Charles Darwin. "For nature," he writes, "time is nothing. It is never a difficulty, she always has it at her disposal; and it is for her the means by which she has accomplished the greatest as well as the least of her results. For all the evolution of the earth and of living beings, nature needs but three elements—space, time, and matter."[83]

In regard to the factors of evolution, Lamarck emphasized the indirect action of the environment in the case of animals, and the direct action in the case of plants. The former are induced to react and thus

[80]Thomson, op. cit., pp. 219-220.

[81]Botanic Garden, 1791, Zoonomia, 1794-96; Phytologia, 1800; Temple of Nature, 1802. It is said that Paley's famous "Natural Theology" was written to counteract the influence of the Zoonomia.

[82]Zoonomia, 1st ed., p. 503. Cf. E. Krause: Life of Erasmus Darwin, with a Preliminary Notice by Charles Darwin. 1879.

[83]Hydrogéologie, 1802.

adapt themselves, while the latter, without a nervous system, are moulded directly by their surroundings. And, so Lamarck believed, such bodily modifications—acquired characters—are transmitted to the next generation and bring about the evolution of organisms.[84]

Through the influence of Cuvier, and the relative weakness of Lamarck's successors—the foremost was Etienne Geoffroy-Saint-Hilaire (1772-1844)[85]—the French School of evolutionists dwindled to practical extinction, while in Germany, Goethe (1749-1832), the greatest poet of evolution, and Treviranus (1776-1837) "brilliantly carried the argument without carrying conviction," for the man and the moment must agree. Then in England the uniformitarian ideas of Hutton (1726-1797), elaborated by Lyell (1797-1875) in his "Principles of Geology, being an attempt to explain the former changes of the Earth's surface by reference to causes now in action" (1830-1833), created an epoch in geology. The prevailing doctrine of cataclysms, emphasized among biologists especially by Cuvier, gradually gave place to that of uniformity—an orderly evolution of the Earth—and paved the way for the next logical step—the evolution of the Earth's inhabitants.[86]

It has been truly said that the idea of development saturated the intellectual atmosphere. But intrenched prejudices which hampered the acceptance of evolution in the inorganic world were immeasurably augmented when the world of life was approached, and only an overwhelming amount of scientific evidence, impartially and convincingly presented could carry conviction.[87] This, in part, accounts for the slight influence of the work of the earlier evolutionists, as well as for the reception accorded the evolutionary views expressed anonymously in the Vestiges of the Natural History of Creation[88] by Chambers (1802-1871). The ten editions of this work (1844-1860) created a furor, especially in England, and were opposed alike by biologist and layman.

The case for evolution at the time, as it appeared to the erudite Whewell, is thus summarized in the first edition (1838) of his well known "History of the Inductive Sciences" and reiterated in the third edition (1857): "Not only is the doctrine of the transmutation of species in itself disproved by the best physiological reasonings, but the additional assumptions which are requisite, to enable its advocates to apply it to the explanation of the geological and other phenomena of the earth, are altogether gratuitous and fantastical. Such is the

[84]Philosophie Zoologique, 1809. English trans. by H. Elliot, 1914. Osborn, op. cit., pp. 165-167. A. S. Packard: Lamarck, the Founder of Evolution, 1901.

[85]Philosophie Anatomique, 1818.

[86]J. W. Judd: The Coming of Evolution, 1910.

[87]Cf. A. O. Lovejoy: The Argument for Organic Evolution before "The Origin of Species." Pop. Sci. Monthly, 75, 1909.

[88]A. Ireland: Introduction to the 12th Edition of the "Vestiges," 1884.

judgment to which we are led by the examination of the discussions which have taken place on the subject."[89]

And then appeared the greatest work of Charles Darwin (1809-1882)—the result of twenty years' labor. The Origin of Species (1859) presented a huge amount of data which most reasonably could be explained by assuming the origin of existing species by descent with modifications from others, and also offered as the modus operandi of their origin the theory of "natural selection, or the preservation of favored races in the struggle for life." In Darwin's words: "As many more individuals of each species are born than can possibly survive, and as, consequently, there is frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance any selected variety will tend to propagate its new and modified form."

Facts and theories had been brought forward before in support of evolution—indeed the theory of natural selection had been suggested before Darwin's time and again independently by Wallace (1822-1913) just as Darwin was completing his long studies preparatory to publication.[90] But the stupendous task of thinking evolution through for the endless realm of living nature remained to be done, and Darwin did it convincingly by his brilliant, scholarly, open-minded, and cautious marshalling and interpreting of data.[91]

It was the combination of the facts and the theory to account for the facts which won the thinking world to organic evolution and "made the old idea current intellectual coin." Darwin supplied the Ariadne thread which led from the maze of transcendental affinity to genetic continuity. Now we know that evolution is a bird's-eye view of the results of heredity since the origin of life and that the facts of inheritance hold the key to the factors of evolution.

Darwin spent the twenty years subsequent to the publication of the Origin of Species, as he had spent the preceding twenty years, in study and research, the results of which appeared in nine additional volumes. Three of these perhaps may be singled out as primarily an elaboration of the "Origin": The Variation of Animals and Plants under Domestication (1868), The Descent of Man (1871) and The Expression of the Emotions (1872). Singly and collectively these volumes are a monu-

[89]3d Ed., Vol. 3, p. 481.

[90]A. R. Wallace: The Origin of the Theory of Natural Selection. Reply on receiving the Darwin-Wallace medal of the Linnean Society, July, 1908. Pop. Sci. Monthly, Apr. 1909, p. 396. J. Hooker: The First Presentation of the Theory of Natural Selection. Op. cit., p. 402.

[91]Cf. the Darwin Centennial Number of the Pop. Sci. Monthly, April, 1909.

ment to genius and labor. Erasmus Darwin was wont to say that the world is not governed by brilliancy but by energy. His grandson revolutionized biological thought through their combination.

Among Darwin's early converts from the ranks of professional biologists must be mentioned Huxley (1825-1895)[92] and Hooker (1817-1911) in England, Haeckel (1834-1919) and Weismann in Germany, and Gray (1810-1888) in America—men with the courage of their convictions when courage was necessary, whose support did so much for the promulgation of evolutionary ideas.

> "Thoughts that great hearts once broke for, we
> Breathe cheaply in the common air."

Today no representative biologist questions the fact of evolution—"evolution knows only one heresy, the denial of continuity"—though in regard to the factors there is much difference of opinion. It may well be that we shall have reason to depart widely from Darwin's interpretation of the effective principles at work in the origin of species, but withal this will have little influence on his position in the history of biology. The great value which he placed upon facts was exceeded only by his demonstration that this "value is due to their power of guiding the mind to a further discovery of principles." Darwin brought biology into line with the other inductive sciences, recast practically all of its problems, and instituted new ones.

Such, in briefest form, is a survey of the epochs and epoch-makers in biological progress—a mere glance of the biologist into the past "to the mountains whence cometh his strength." Building upon these foundations the biological sciences are developing with amazing rapidity at the present time chiefly through the cumulative influence of an all pervading desire of students of life phenomena to observe nature at work—actually to control and modify biological processes. Today the investigator insists upon interrogating nature experimentally and observing the modus operandi. In a word, the modern biological ideal is to construct an account of the living organism which can be verified by actual observation provided the proper conditions are afforded. Biology has emerged from the phase of development in which the descriptive note was dominant and has become in fact an experimental science.

[92]T. H. Huxley: Darwiniana, Collected Essays, Vol. 2. Life and Letters, edited by his son, 1901.